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COMPUTATION OF INFRARED TRANSMITTANCES IN THE TROPOSPHERE USING SATELLITE VALUES OF PRECIPITABLE WATER: PRELIMINARY METHOD

May 1992

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Transmittance in the thermal infrared may be estimated from various in situ and remote techniques using ground-based or airborne sensors. However, estimating transmittance in the troposphere from data gathered by sensors on space platforms remains a problem, especially over land surfaces. This report presents a preliminary method for computing thermal infrared transmittance over a horizontal, vertical, or slant path. This method uses estimates of precipitable water from satellite data combined with sounding data from satellite or other sources. A brief description of the technique and a brief sensitivity analysis provide a basic understanding of the method. Profiles of specific humidity are computed from actual atmospheric profiles or climatological data and then adjusted according to satellite estimates of total precipitable water. Temperature and humidity data at each pressure level provide input to equations of the types found in LOWTRAN. These equations yield estimates of thermal infrared transmittance for user-specified path lengths.

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1. INTRODUCTION

Determining atmospheric infrared transmittance in the troposphere is a major problem for remote or denied areas. Air or space-based platforms may carry in situ devices or remote sensing instruments. However, methods to estimate infrared transmittance by using data from space platforms remain a problem, especially over land surfaces. This report presents a preliminary method to compute thermal infrared transmittance over a horizontal, vertical, or slant path. The method uses estimates of precipitable water from satellite data combined with sounding data from satellite or other sources. If sounding data are unavailable, or too distant in space or time from the area or time of interest, then climatological profile data may be used to provide an approximate estimate. A brief description of the technique and a brief sensitivity analysis provide a basic understanding of the method. Profiles of specific humidity are computed from actual atmospheric profiles or climatological data and then adjusted according to satellite estimates of total precipitable water.

2. DESCRIPTION OF METHOD

2.1 Overview

The preliminary technique uses the relation between water vapor and infrared extinction in the atmosphere. Algorithms of the types found in LOWTRAN (low resolution transmittance and radiance) may be used to compute infrared transmittance in a horizontally stratified atmosphere (Kneizys et al., 1980, 1983, 1988). Temperature and humidity data at each pressure level of an atmospheric sounding provide input to equations similar to those found in Kneizys et al. (1980). The older version of LOWTRAN used standard type variables (for example, vapor pressure in atmospheres). The accuracy in the thermal infrared is virtually the same as in Kneizys et al. (1983), and the algorithms are the same in Kneizys et al. (1988) and Kneizys et al. (1983). These equations yield estimates of thermal infrared transmittance for user-specified horizontal, vertical, or slant path lengths. The preliminary version assumes a horizontally homogeneous layer at a given pressure (that is, horizontally stratified atmosphere). The simple integration techniques of this approximate method assume constant or only slowly varying transmittance over spectral intervals of up to 20 cm^{-1}. Nominally this method can give results for smaller spectral intervals (to 1 cm^{-1}). However, for this investigation 20 cm^{-1} intervals were used and did not appear to degrade the results in this case.

Generally, atmospheric soundings from various sources may be used, but for applications to remote areas the primary sources would be satellite soundings, soundings derived from aircraft or unmanned aerial vehicle (UAV) data, dropsonde profiles, or a combination of the above (Cogan, 1990). The resultant sounding provides temperature (T) and humidity (h) values at given pressure levels, which may be used to compute specific humidity (q). From values of q one may compute precipitable water (PW) for layers or for the entire vertical extent of the sounding (total or integrated PW). Integrated values of PW may be compared to values derived from satellite imagery. The sounding amount (not the shape of the distribution curve) is adjusted according to the ratio of the estimate from satellite imagery (called satellite estimate or value in this report) to the

value computed from the sounding. If sounding data are not available for the time and area of interest, then climatological profiles for the most appropriate region and season may be used. The accuracy most likely will degrade, but useful gradient information may be possible.

Several investigators using, for example, transmittance ratios (total through entire atmosphere) have developed techniques for satellite estimates of PW. Chesters et al. (1983) and chesters et al. (1987) used split window radiances from the Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) carried on Geostationary Operational Environmental Satellites (GOES). Jedlovec (1989) and Kleespies and McMillin (1990) developed methods that used data from both the VAS and the Advanced Very High Resolution Radiometer (AVHRR) carried by National Oceanographic and Atmospheric Administration (NOAA) satellites. Jedlovec (1989) derived his method by using aircraft data and then applied it to satellite values. Kleespies and McMillin (1990) reported correlations as high as 0.85 (AVHRR) and 0.92 (VAS) relative to PW from radiosonde data. Ongoing work in this area could lead to improved absolute accuracies.

2.2 Transmittance Algorithms

The author assumed that atmospheric soundings provide profiles of T (K), h (%), and z (m) at several pressure levels. Pressure (p) has units of hPa (= mbar). Values of h are converted to values of absolute humidity q (g m^{-3}) through the standard equations found in references such as Ludlam (1980). First, saturation vapor pressure (e_s) in hPa is computed.

$$e_s = 6.108 \exp(17.27(T - 273.16)/(T - 35.86)) \qquad (1)$$

Then e_s is used in the computation of q by the formula:

$$q = (e(10^6)/TR_v)h/100, \qquad (2)$$

where R_v is the gas constant for water vapor. Climatological profiles may include values of q, in which case the above equations are not required. From the q profile, PW for each layer (i) in units of g cm^{-2} is computed from

$$(PW)_i = 0.1(z_{i+1} - z_i)(q_{i+1} + q_i)/2. \qquad (3)$$

The layer values of PW are summed to get the total PW. The ratio of the satellite-measured value of PW to the total PW from the sounding is used to scale the values of q for each pressure level or height.

The resultant profile of q is used with equations of the types found in Kneizys et al. (1980) for computing transmittance for the mean wave number of a narrow

spectral interval. First, however, e (in units of atm) is computed using a variation of equation (2).

$$e = qTR_v(10^{-6})/p_0,$$

where p_0 is standard pressure (= 1013.25 hPa). A LOWTRAN water vapor parameter (w) (the effective water vapor absorber amount per unit path length in g cm^{-2} atm km^{-1} at altitude z) is computed using the following:

$$w = 0.1q[e(\exp[6.08(296/T - 1)]) + 0.002(p - e)], \tag{4}$$

where p is in units of atm. The water vapor attenuation coefficient (C_s) in g^{-1} cm^2 atm^{-1} (≈ absorption in the thermal infrared), as defined in Kneizys et al. (1980) for a thermal infrared wave number (ν) in the 8 to 14 μm wavelength region at a temperature of 296 K, is given by

$$C_s = 4.18 + 5578 \exp(-0.00787v). \tag{5}$$

Finally, the transmittance (τ) for a given thermal infrared wave number is computed from a variation of the standard equation

$$\tau = \exp(-C_s w d_h). \tag{6}$$

This procedure should be valid for a narrow wave number band in the thermal infrared to a useful accuracy. For example, τ for the mean wave number of a 20-cm^{-1} band, as used in LOWTRAN, provides a reasonable estimate of τ for that interval. The assumption is that transmittance is constant or only varies slowly and fairly smoothly over a 20-cm^{-1} interval. However, the use of LOWTRAN to compute monochromatic transmittances (as for a laser) may lead to serious errors (McClatchey et al., 1972). The same warning also applies to the method this author devised, which was derived from LOWTRAN.

The equations for carbon dioxide, ozone, and noncontinuum water vapor were derived from LOWTRAN equations for "uniformly mixed gases" (for example, carbon dioxide) and water vapor (Kneizys et al., 1980). Transmittance over an interval of 20 cm^{-1} is computed from an equation of the form $\tau = f(C_n\ w^*\ D_s)$, where C_n is a wave number dependent absorption coefficient, w^* is an equivalent absorber density, and D_s is the atmospheric path.

$$w^* = w\left[\frac{p(z)}{p_o}\sqrt{\frac{T_o}{T(z)}}\right]^m , \tag{7}$$

where p_o and T_o correspond to standard pressure and temperature (1 atm = 1013.25 hPa, 273.16 K). m has values of 0.9, 0.75, and 0.4 for water vapor, carbon dioxide, and ozone, respectively. In LOWTRAN the form of the function for τ and the parameter m were determined empirically using laboratory transmittance data and molecular line constants (Kneizys et al., 1980). Curves were computed based on these data and presented in Kneizys et al. (1980) for τ (graphed as log to the base 10 of τ), C_n, and absorber concentrations. The curve of $\log_{10} \tau$ for ozone is different from that for water vapor (noncontinuum) and the uniform mixed gases, but the basic form is similar. The units for the C_n and concentrations differed, but can be converted to "standard" units through the use of relationships given in McClatchey et al. (1972).

The approach for aerosols was based on the technique of Kneizys et al. (1980). This preliminary report considers only distributions for land aerosols (rural and urban). Later, Kneizys et al. (1983) improved the distribution for the lowest 2 km over land by using routines based on Heaps (1982). More recent updates as noted in Kneizys et al. (1988) should improve matters further, but no documentation existed when this report was prepared. However, the earlier approach should be sufficiently accurate for the research described in this report.

Kneizys et al. (1980) presented profiles of aerosols for various situations, including the rural and urban curves, maritime distributions, and curves for after volcanic eruptions. Seasonal and high humidity differences were included. However, for the preliminary effort described here, mean curves for the basic profiles for land, rural and urban, were thought to be sufficient. Transmittance was then calculated through an equation of the form τ(aerosol) = exp(-extinction coef * haze scale factor value * distance).

In the program of this report the aforementioned curves were approximated through piecewise linear or power law fits, or a combination of both. Other fits may produce a closer approximation, but the ones chosen gave a sufficiently good fit for this initial investigation.

2.3 Precipitable Water Adjustment

PW is calculated from q for layers determined by the sounding levels, and then summed to obtain a total integrated value for the sounding (PW_s). Values of PW may be calculated from satellite imagery (PW_i) by a method such as the methods developed by Chesters et al. (1983), Chesters et al. (1987), Jedlovec (1989), and Kleespies and McMillin (1990). Each layer value of q (q linearly related to PW) is then multiplied by the ratio PW_i/PW_s. The adjusted layer values of q are used in computing τ by the method described above. If more than one sounding is close to a particular location, then appropriate mean values for computing the ratio should be used. However, such a procedure had not been incorporated in this preliminary technique.

3. COMPARISONS AND SIMULATIONS

3.1 Comparisons

The approximate method of this report for computing thermal infrared transmittances was compared with LOWTRAN 7 (PC version) for vertical paths from the surface to 14 km. In particular the spectral intervals covered by channels 4 and 5 of the AVHRR were chosen for the comparison (885-971 and 800-870 cm^{-1}). For this comparison the spectral responses of the actual instrument were not considered (that is, step function response used), and a rural aerosol with a 23-km visibility was assumed.

As noted above, the calculations of this report did not account for sensor response as did those for the GENLN2. However, sample computations with the U. S. standard and tropical atmospheres suggested that leaving out the response function (that is, assuming constant response across the interval) only led to relatively small errors in results from the approximate method of this report and LOWTRAN. The errors were < 0.002 for channel 4 and ≤ 0.01 for channel 5. All values that were computed with the sensor response included were higher, and magnitudes were larger for the tropical atmosphere. Nevertheless, the closeness of the approximate method and GENLN2 results, with the possible "errors" considered, may be fortuitous. However, the method apparently can produce useful results for a cloud free line of sight.

Table 1* shows the results of the comparison for a few of the "standard" atmospheres. The differences in τ were small to moderate except for the much larger difference (over 0.06) for the subarctic winter atmosphere. Transmittances from both LOWTRAN and the program of this report were compared to those from a line-by-line method (GENLN2) as reported by Saunders and Edwards (1989). Table 2 compares values of τ computed over a vertical path from 0 to 100 km for the U.S. standard atmosphere with an urban aerosol by the approximation program of this report, the PC version of LOWTRAN 7, and the GENLN2 line-by-line program. The GENLN2 values are listed as presented in Saunders and Edwards, that is, rounded to the nearest 0.01.

Neither LOWTRAN nor the approximate method produced values equal to the GENLN2 results, but nearly all the approximation values were closer. A comparison of the results shown in table 1 with those derived from data presented in Saunders and Edwards (1989) suggested that, except for the tropical atmosphere, the approximation values were closer to the GENLN2 output (especially for the subarctic winter case). In all cases the line-by-line calculations led to higher values of τ than either of the lower resolution programs. However, different line-by-line models may not yield the same values. Saunders and Edwards noted that Chedin et al. (1988) reported that for nadir paths in the 15-μm region various transmittance models only agree to within 2 percent in τ.

*Tables and figures are presented at the end of the text.

3.2 Modified Method

The approximate method was analyzed and compared to the line-by-line model for several atmospheric constituents. The main differences from the line-by-line results were for water vapor, especially continuum absorption. The differences were nonlinear, and they increased with increasing water vapor amount. A minor change to the wave number coefficient in equation (5) from -0.00787 to -0.00817 resulted in significantly closer values for the more moist atmospheres, especially for the tropical case. Table 3 shows some results of the comparison between the GENLN2 and modified approximate method. For channel 5 (800-870 cm^{-1}) the two sets of values agreed to within 0.004, and for channel 4 (885-971 cm^{-1}) the largest difference was 0.011. Both maximum differences were computed for the subarctic winter atmosphere. The values presented in table 3 may be compared with LOWTRAN 7 and unmodified approximate results in table 1.

Saunders and Edwards (1989) published results by absorber/scatterer for the U. S. standard atmosphere that were compared to those computed by the modified method. As seen in table 4 the two methods produced values that agree reasonably well. Certain of the Saunders and Edwards results were presented to the nearest 0.01 and others to 0.0001; the former values are shown as printed and the latter are rounded to the nearest 0.001, as was the output from the approximate method. The maximum difference apparently did not exceed about 0.01, and would have been smaller if the response curves had been used.

3.3 Simulations

Various simulations were made with the approximate method to get an idea of the likely errors in τ that would be associated with typical errors in PW from satellite data. Chesters et al. (1983) reported an overall rms error in total PW computed from VAS data of about ± 1.0 g cm^{-2} over a range of PW values from 1.7 to 5.5 g cm^{-2}. In a later paper by Chesters et al. (1987) the error was reduced to ± 0.6 g cm^{-2}. Kleespies and McMillin (1990) found a standard difference of around 0.44 g cm^{-2} when their technique was applied to AVHRR data, and 0.39 g cm^{-2} for VAS data. For all of the above methods, single comparisons with data from individual rawinsondes gave differences of up to around 2 or 3 g cm^{-2}. For this report τ values were calculated for the tropical and mid-latitude summer atmospheres where the total PW was changed by ± 0.5 and ± 1.0 g cm^{-2}. The results of those computations for the mid-latitude summer are shown in table 5. Figure 1 shows the variation of τ for horizontal paths of 3 km at each level up to 6 km for channel 5 for the same model atmosphere with a PW variation of ± 0.5 g cm^{-2}. As indicated in the figure the differences in horizontal τ at lower levels can be significant for the given "errors" in PW.

Figures 2 and 3 present curves similar to those of figure 1 for the subarctic winter and tropical atmospheres. The curve in figure 2 for PW = 0.000 g cm^{-2} shows τ values for a completely dry atmosphere. Among the standard atmospheres the greatest change in τ for a change in PW of ± 0.5 g cm^{-2} apparently occurred for the fairly moist (PW = 2.977 g cm^{-2}) mid-latitude summer atmosphere. A slightly smaller change occurred for the less moist (PW = 1.448 g cm^{-2}) U.S. standard atmosphere (not shown). Figure 4 was calculated for a real rawinsonde sounding launched about 16 Z on 26 September 1980 at Dayton, Ohio (Bradford et al., 1982). A fairly strong subsidence inversion capped a modestly moist layer

below 2 km. The values of τ below 2 km exhibit changes greater than those shown by any of the standard atmospheres of figures 1 through 3 and the U. S. standard atmosphere when PW is varied by ± 0.5 g cm^{-2}. This very limited comparison with real data supports the idea that use of climatological data to estimate τ would lead to less accurate results and that actual sounding data should be used whenever possible.

4. CONCLUSION

A preliminary technique was developed for estimating transmittance in the thermal infrared in the troposphere by using satellite-derived values of PW along with profile data that are not too distant in space or time. The computer model was written in the "C" computer language and can run on an 80286-based computer (with math coprocessor) in a few seconds. Furthermore, Chesters et al. (1983) noted that relative accuracies are very good compared to absolute accuracies. Consequently, adjusting a coincident satellite-derived value of PW to that extracted from the profile data may allow a useful description of the surrounding moisture field.

The apparent accuracy of the approximate method for computing τ of about 0.01 relative to a line-by-line model seems reasonably useful for many cloud free atmospheres. Present plans include a further comparison with the very recent version of MODTRAN (moderate resolution transmittance and radiance) that can run on an 80386-based computer (with math coprocessor) and real transmittance data (when available) to further refine the method. However, the primary source of error appears to arise from the satellite estimates of PW. An error in PW of ± 0.5 g cm^{-2} can lead to errors in τ for a 3-km horizontal path that may exceed 0.10 (figure 4). Therefore, further work will concentrate more on improving the technique for estimating PW from satellite imagery.

TABLE 1. RESULTS FROM TRANSMITTANCE COMPUTATIONS USING LOWTRAN 7 (L) AND THE APPROXIMATE METHOD (A)*

Atmosphere	Model	Transmittance ch 4	Transmittance ch 5
Tropical	*L*	0.516	0.368
	A	0.509	0.363
Mid Latitude Summer	*L*	0.641	0.522
	A	0.662	0.541
Subarctic Winter	*L*	0.870	0.850
	A	0.941	0.927

*The PC version of LOWTRAN was used.

TABLE 2. TRANSMITTANCE RESULTS USING GENLN2 (G), LOWTRAN 7 (L) AND THE APPROXIMATE METHOD (A)*

Model	Transmittance ch 4	Transmittance ch 5
G	*0.85*	*0.80*
L	*0.792*	*0.737*
A	*0.851*	*0.792*

*The results from GENLN2 (a line-by-line model) were presented in Saunders and Edwards (1989). All results were for the U.S. standard atmosphere.

TABLE 3. TRANSMITTANCE COMPUTED FOR AVHRR CHANNELS 4 AND 5 FOR THREE MODEL ATMOSPHERES

Ch/Model		Atmosphere		
		SAW	MLS	TROP
ch 4	A	0.942	0.686	0.542
	G	0.931	0.691	0.552
ch 5	A	0.930	0.579	0.410
	G	0.926	0.580	0.413

A - approximate model (modified)
G - GENLN2 line-by-line model
SAW - subarctic winter
MLS - mid-latitude summer
TROP - tropical
Ch 4 - 885-971 cm^{-1}
Ch 5 - 800-870 cm^{-1}

TABLE 4. TRANSMITTANCE COMPUTED FOR AVHRR CHANNELS 4 AND 5 FOR IMPORTANT ABSORBERS/SCATTERERS

Ch/Model		Absorber/Scatterer					
		H2O c	H2O l	CO2	O3	Aerosol	Total
ch 4	A	0.925	0.972	0.988	1.000	0.968	0.860
	G	0.93	0.97	0.985	1.000	0.97	0.85
ch 5	A	0.892	0.935	1.000	1.000	0.968	0.807
	G	0.90	0.94	0.996	1.000	0.97	0.80

All values computed using the U.S. standard atmosphere.
A - approximate model (modified)
G - GENLN2 line-by-line model
c refers to continuum absorption and l refers to line absorption.

TABLE 5. TRANSMITTANCES COMPUTED WITH THE APPROXIMATE METHOD USING THE MID-LATITUDE SUMMER ATMOSPHERE

PW ($g\ cm^{-2}$)	Transmittance ch 4	Transmittance ch 5
1.977	0.796	0.718
2.477	0.732	0.631
2.977	0.663	0.545
3.477	0.592	0.458
3.977	0.520	0.377

PW in $g\ cm^{-2}$ was varied by ±0.5 and ±1.0 $g\ cm^{-2}$ relative to the nominal mid-latitude summer value of 2.977 $g\ cm^{-2}$ (total value from 0 to 14 km).

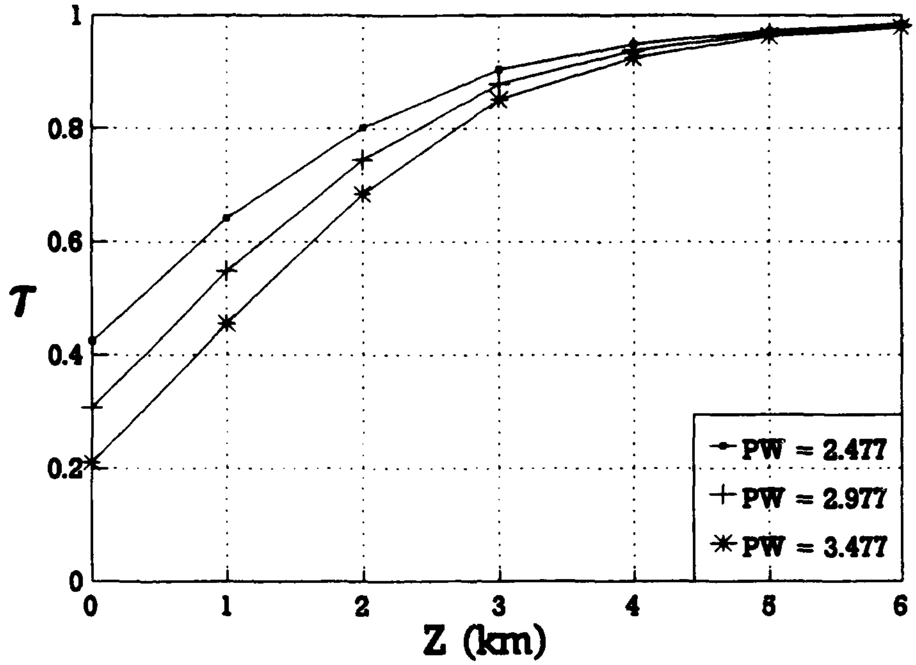

Figure 1. Transmittance (τ) values for channel 5 computed by using the approximate method for the mid-latitude summer atmosphere for 3 km horizontal paths at the indicated heights (Z) for the listed values of PW in g cm^{-2}

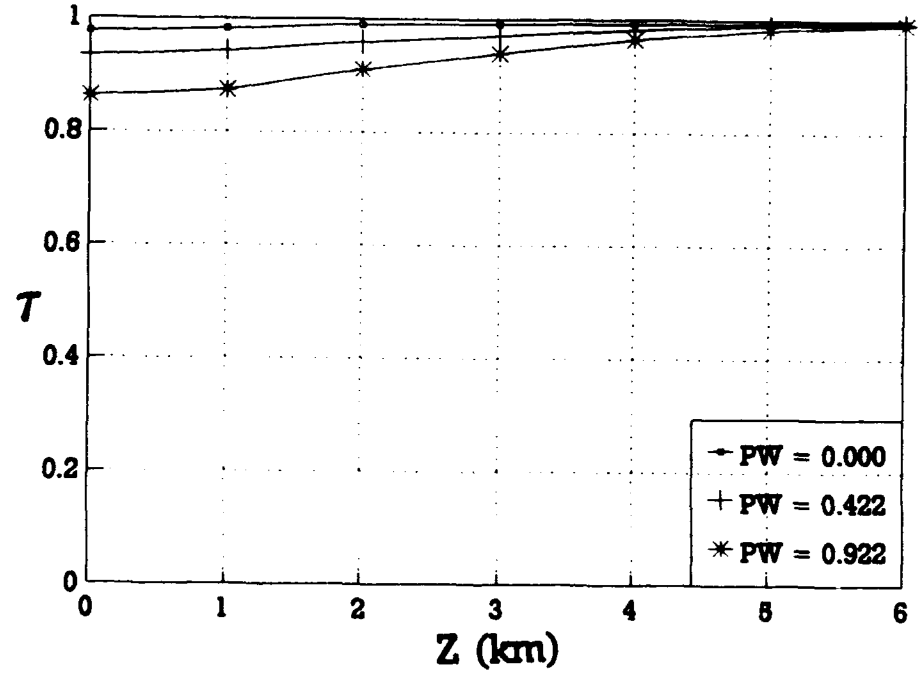

Figure 2. Transmittance (τ) values for channel 5 computed by using the approximate method for the subarctic winter atmosphere for 3 km horizontal paths at the indicated heights (Z) for the listed values of PW in g cm^{-2}.

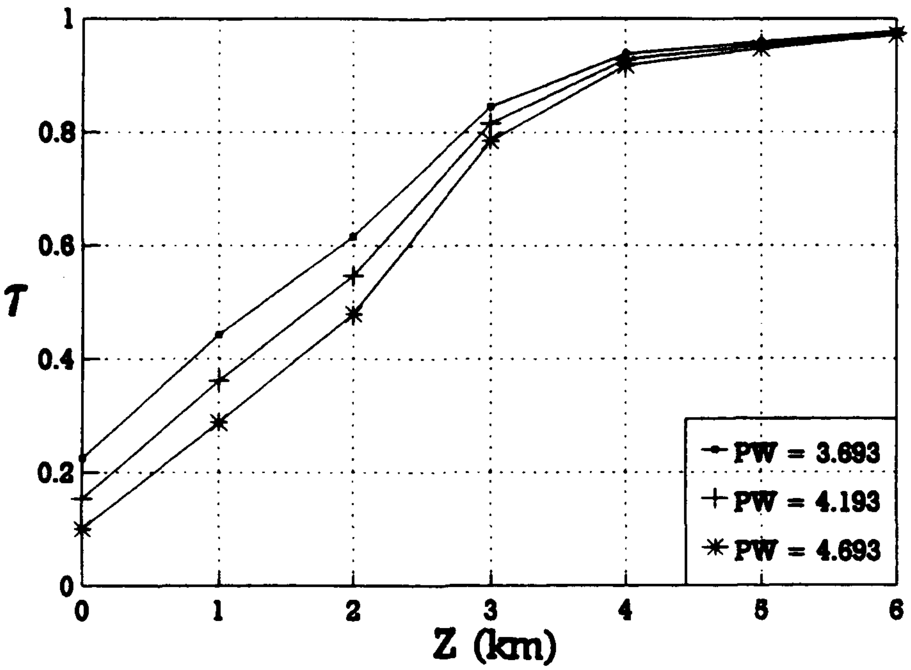

Figure 3. Transmittance (τ) values for channel 5 computed by using the approximate method for the tropical atmosphere for 3 km horizontal paths at the indicated heights (Z) for the listed values of PW in g cm^{-2}.

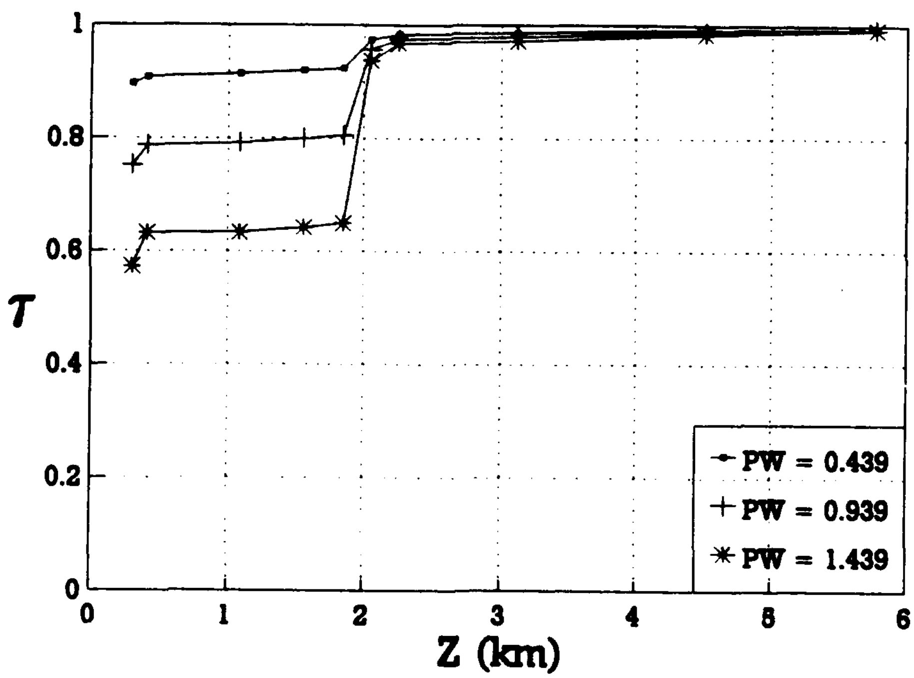

Figure 4. Transmittance (τ) values for channel 5 computed by using the approximate method for an actual sounding (see text) for 3 km horizontal paths at the indicated heights (Z) for the listed values of PW in g cm^{-2}.

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